



Modeling the aging and reliability of solder joints

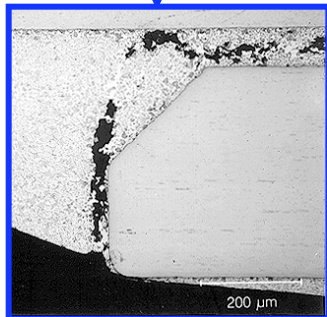
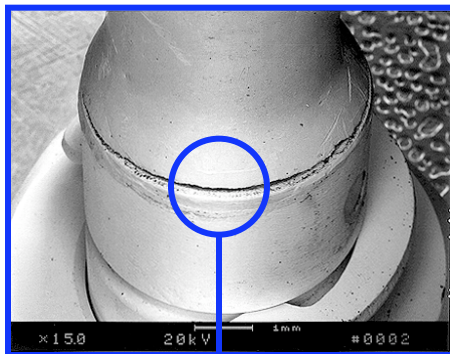
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Aging and failure of solder joints

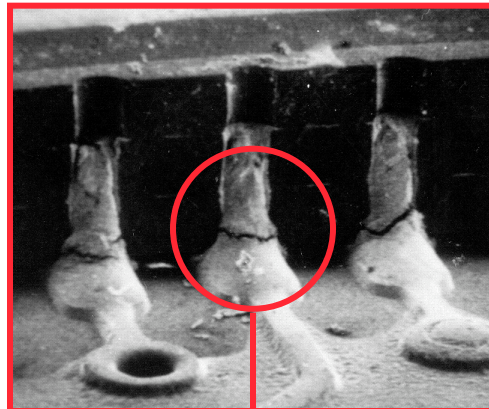
- Typical circuit boards contain thousands of solder joints.
- Solder joints function at a high homologous temperature under thermomechanical fatigue conditions.

→ **Solder joints fail.**

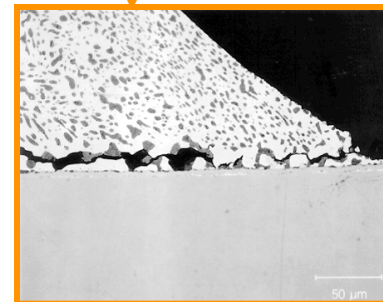
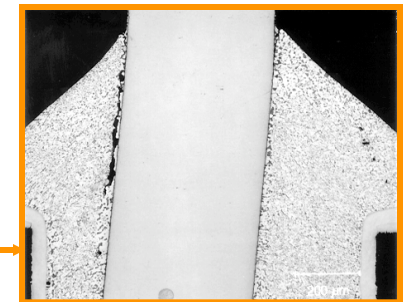
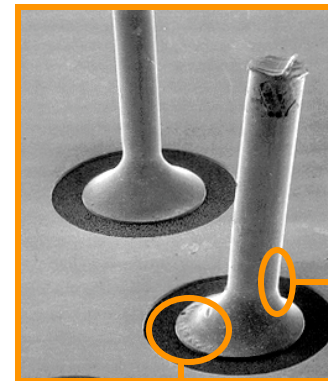
connectors



surface mount



through hole





How big is the problem?

- Studies indicate that **at least 48% of electronics failures** are likely due to solder joint failure.

- Solder joints must remain reliable beyond their initial design lifetimes

Military and commercial aircraft

Satellites

Nuclear and conventional weapons

⇒ Solder joints are a **design** problem:

Design for reliability beyond commercial product lifetimes.

⇒ Solder joints are a **stewardship** problem:

Predict when a component requires replacement - before it fails.



Added complications: New solder technologies

- Legislation and industry standard require change to lead-free solders in future circuit board assemblies.
 - These are new materials, and long-term reliability has not been fully characterized.
 - Many alloy compositions are being considered and used.
 - Surface finish effects are important in these materials.
- New package designs challenge the limits of solder reliability.
 - Higher I/O/finer pitch area-array packages
 - Package-on-package (PoP)
 - Stacked chips
 - System-in-a-package (SIP)
 - Opto-electronic devices
 - High temperature molding compounds
 - High temperature, “green” laminates

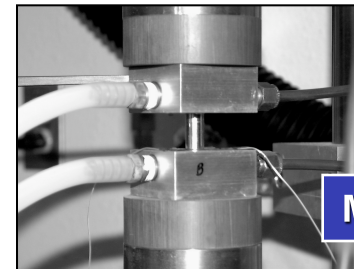
Integrated approach to understanding lifetime prediction and failure in solder joints

Compile **materials properties** data for model input parameters.

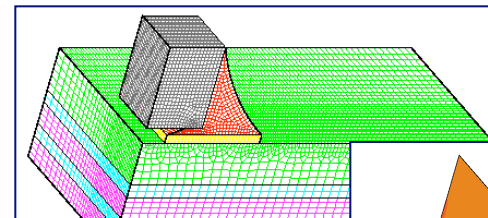
Develop the **computational model**:

- *Constitutive equation*
- *Finite element code (mesh)*
- *Optimization routines*

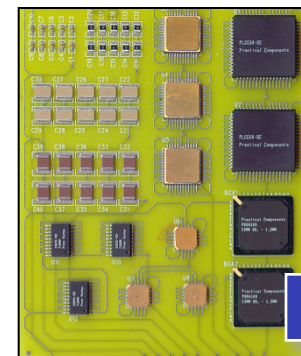
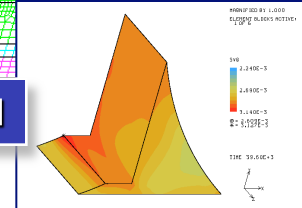
Model validation using limited accelerated aging experiments.



Material Properties

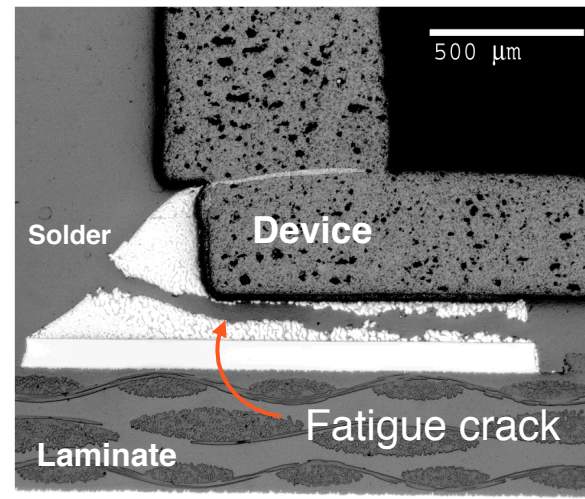
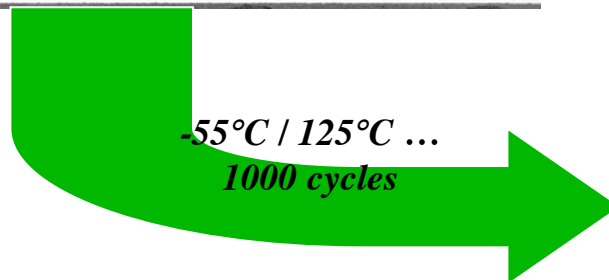
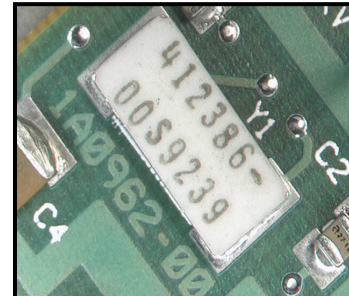
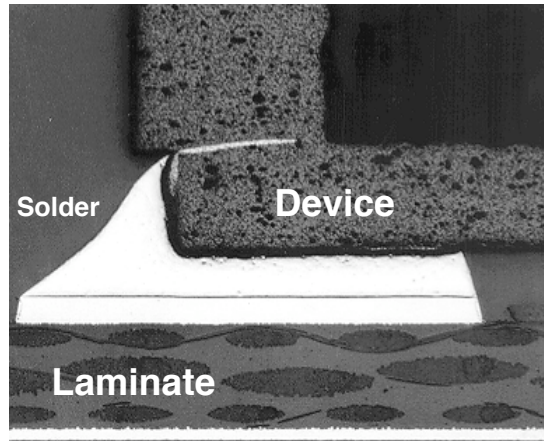


Computational Model



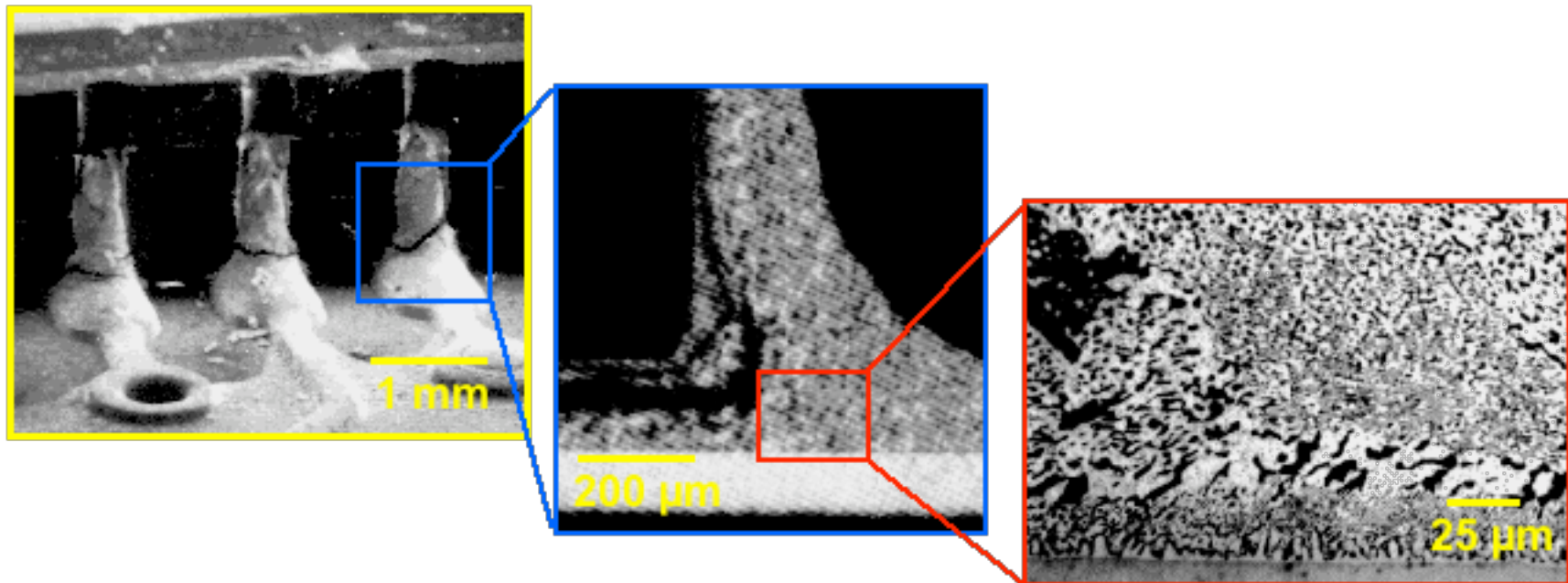
Model Validation

Eutectic Pb-Sn Solders



Why is microstructure important in PbSn solders?

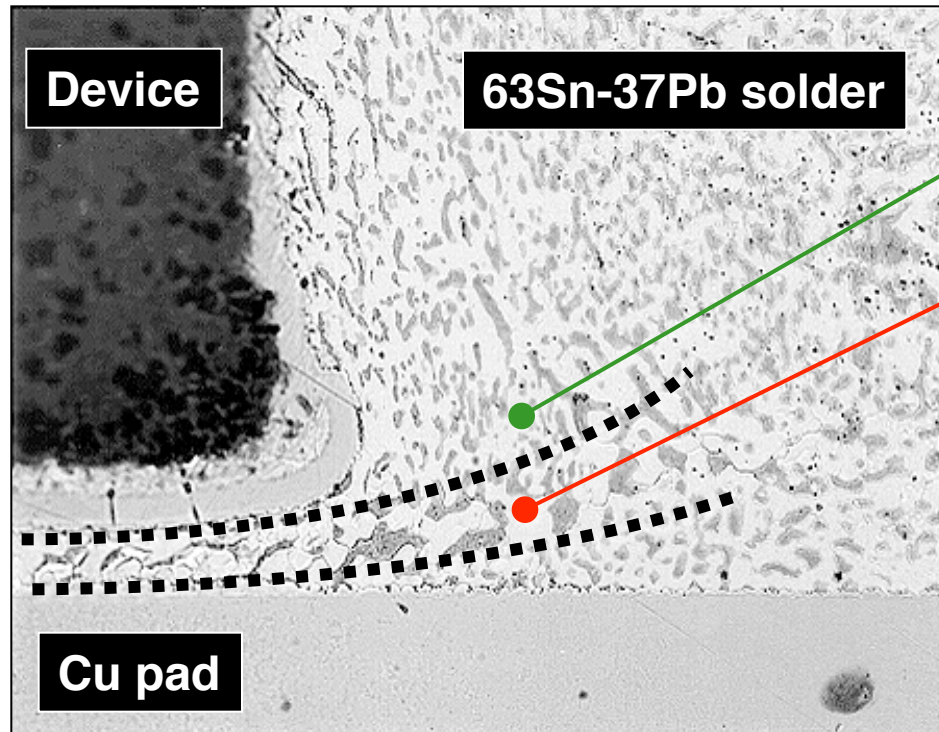
- The coupling between microstructure and mechanical response causes failure.



strain localization → local coarsening → further softening → failure

A microstructural approach to solder modeling

- **Local** microstructure determines the **local** mechanical properties.
⇒ The microstructural metric is λ , the mean Pb-rich phase particle diameter.



$$[d\gamma/dt]_{\text{fine}} = f(\sigma, T, \lambda_{\text{fine}})$$

$$[d\gamma/dt]_{\text{coarse}} = f(\sigma, T, \lambda_{\text{coarse}})$$

The CoMPSIR© Sn-Pb solder fatigue model captures these microstructural effects to predict solder joint lifetimes.



Failure - Lifetime Prediction

A variety of failure criteria are currently being evaluated:

Failure based microstructure

Failure when $\lambda = \lambda_{\text{critical}}$

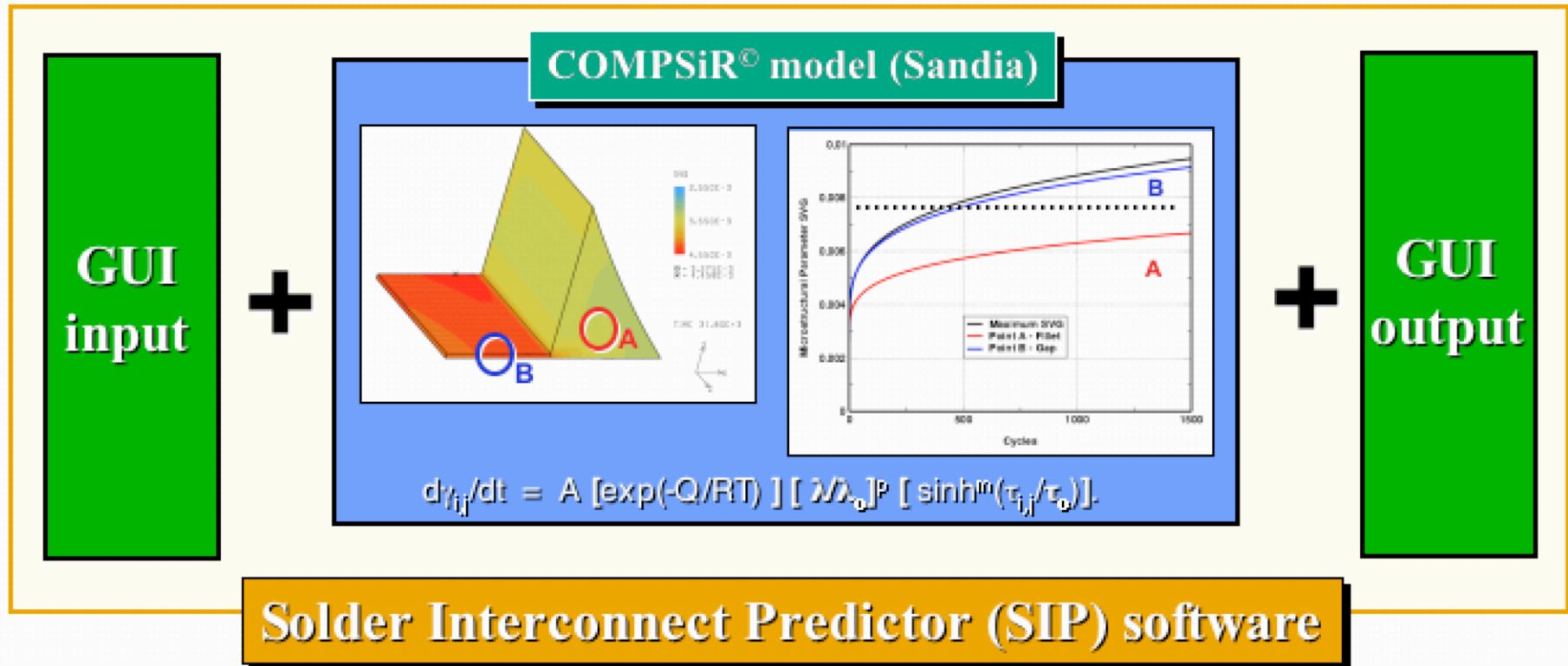
Coffin-Manson

$N_f^{0.51} \Delta\gamma^P = 1.14$ (Solomon, 86)

Continuum damage approach

Failure when $\omega = \omega_{\text{critical}}$

The solder TMF model is incorporated in a desktop design and analysis package.

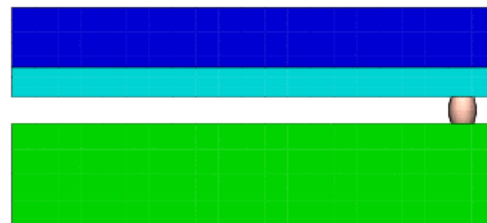
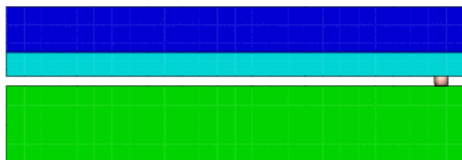
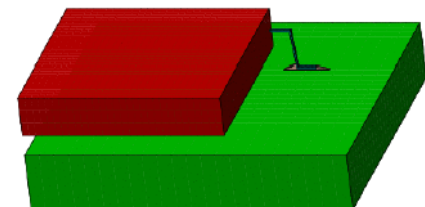
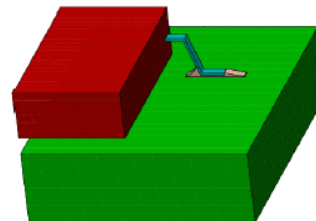
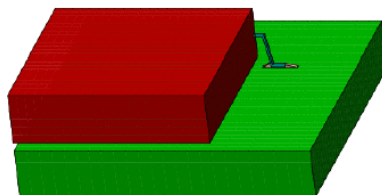
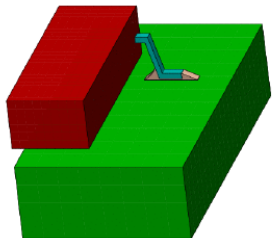
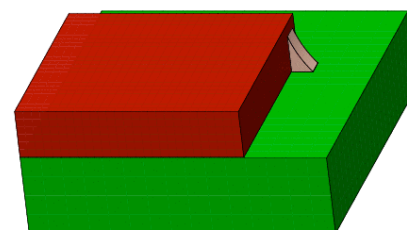
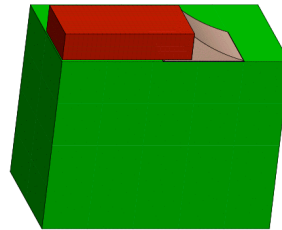
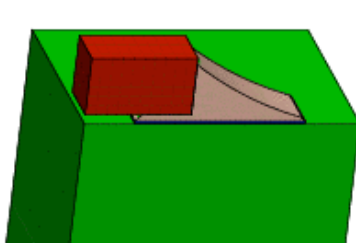


- Linux and Windows packages
- Variety of joint geometries
- Variable dimension joint shapes



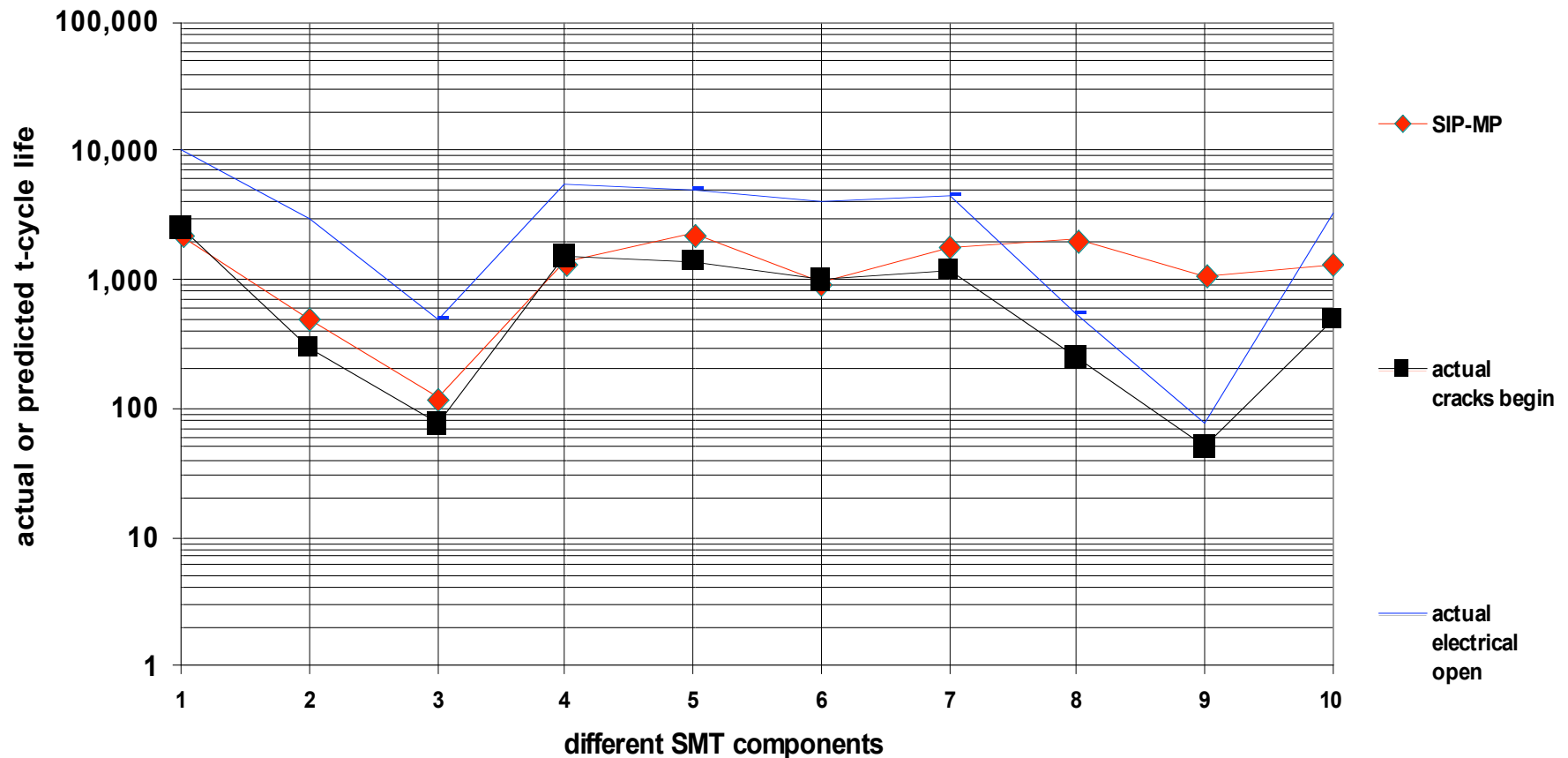
Is the SIP model predictive?

- A Lockheed-Martin sponsored round robin offered the chance to **validate SIP in a blind study** against experimental data for a variety of solder joints.
- Ten solder joint geometries ranged from surface mount to FP to BGA.



SIP Predictions for Solder Round Robin

- Sandia-SIP (**red** line) agreed very well with experiment (**black** line) for most joint types.
- Components 8 and 9 (BGAs) demonstrated mesh refinement issues that we have addressed.





How can we add predictivity?

- The Round Robin results showed that crack initiation precedes failure, often by thousands of cycles (**blue** line).

⇒ Can we model the actual failure process: cracking to open circuit?

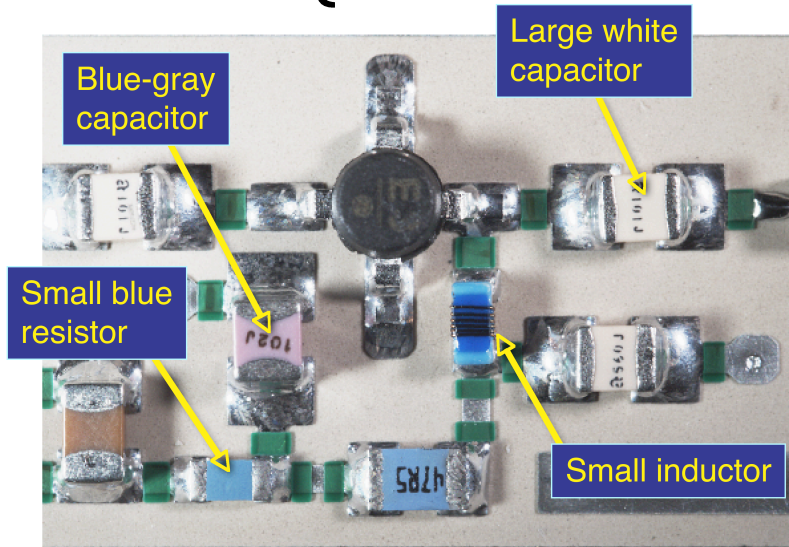
- Fracture propagation is a challenge in FEM implementation, due to stress singularities and nonlinear behavior.
- We take a smeared cracking approach – replace cracked elements with weak elastic material.
 - » When λ gets to critical value of $6.0\mu\text{m}$, elements become weak elastic material with $\sigma = 0.01 \mathbf{E} : \epsilon$.
 - » Dramatic change in element mechanical response changes boundary value problem.
 - » No remeshing needed; no numerical difficulties from introduction of a discrete crack.

How well does it work?

Comparisons to test vehicle experiments

Test vehicle
accelerated aging
conditions

-55°C ... 125°C, 20 min holds;
0, 500, 1000, and 1500 cycles

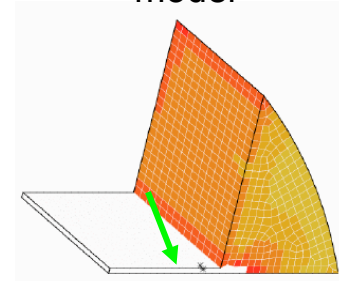
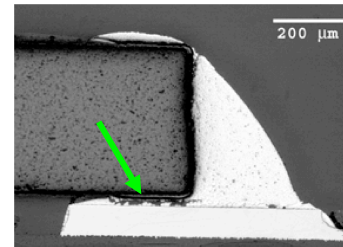


- SIP results for both crack morphology and joint lifetime agree well with experiments on a test vehicle circuit board.

Small blue resistor:

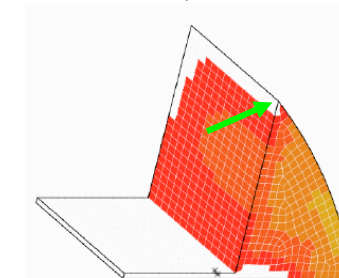
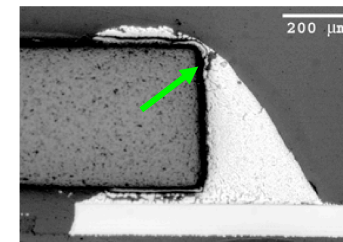
experiment

model



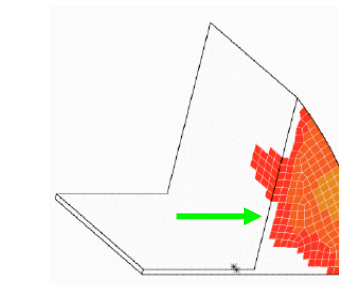
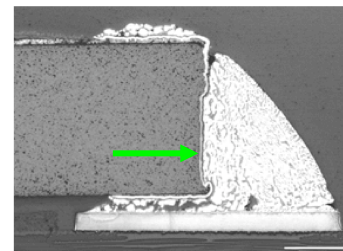
500 cycles

500 cycles



1000 cycles

1000 cycles



1500 cycles

1500 cycles

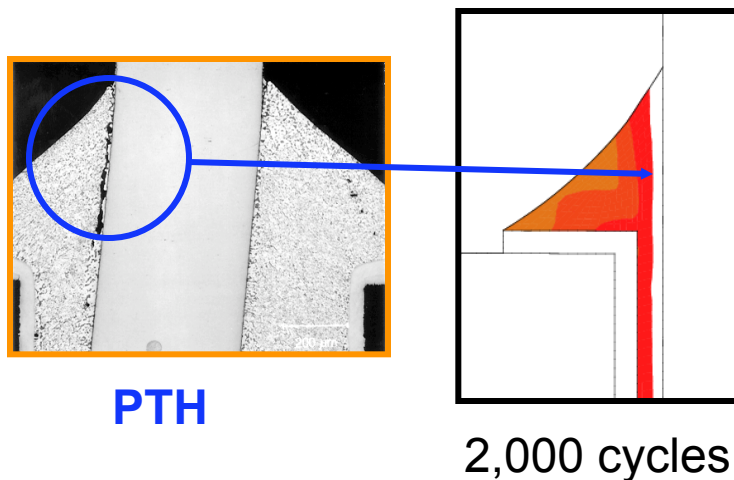
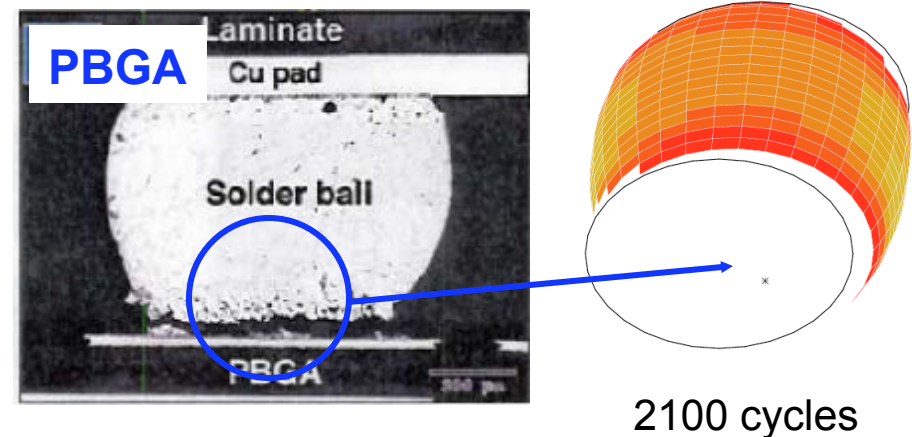
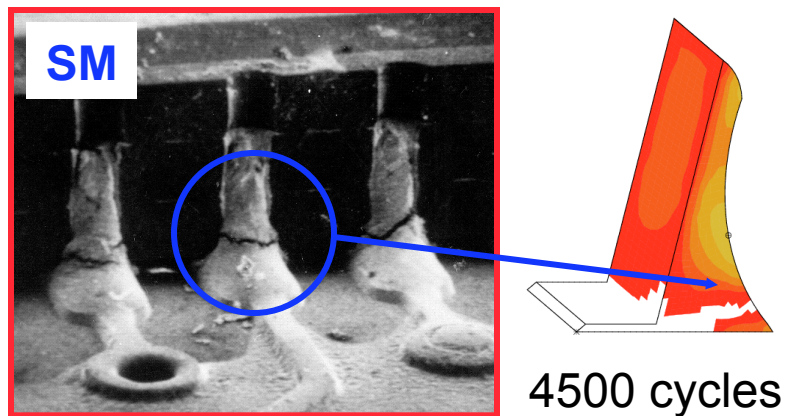
White elements are cracks.



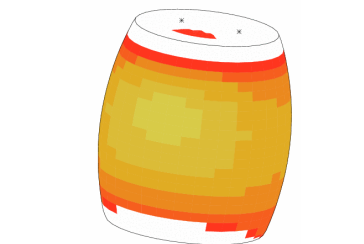
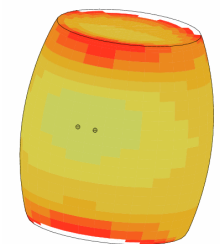
Sandia
National
Laboratories

SIP today

- SIP is used as a predictive design and analysis tool by Sandia, US Navy, Lockheed-Martin, and other customers.



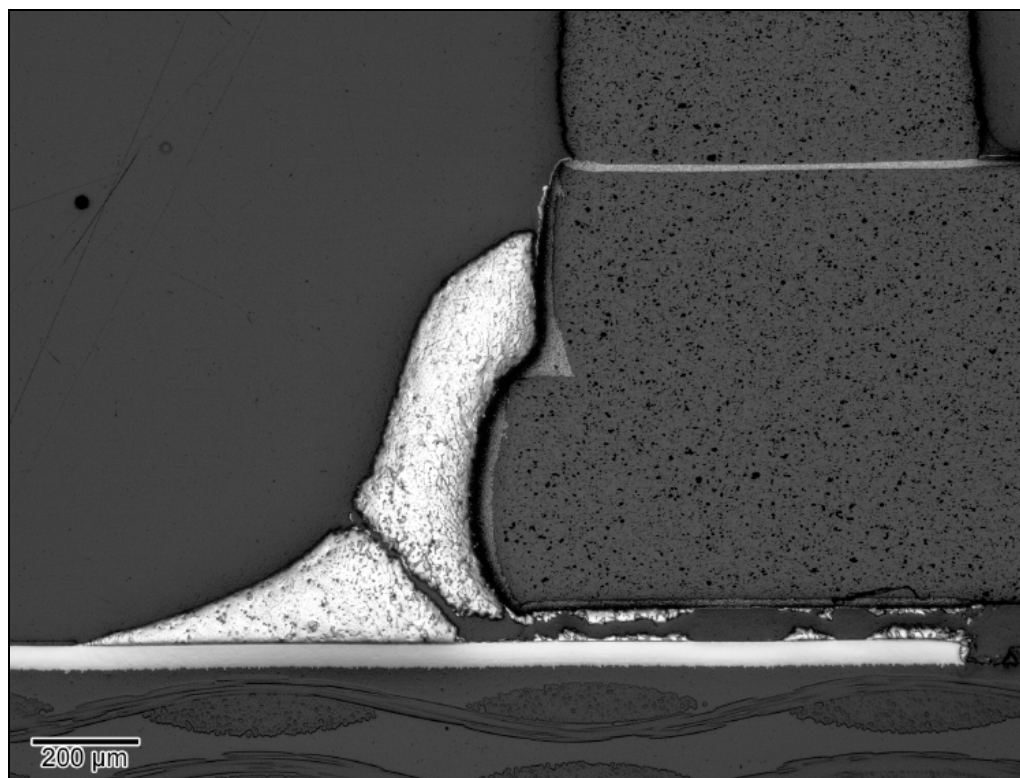
Experiments indicate CBGA failure @ 200 to 300 cycles.



CBGA



Pb-free Solders



Pb-free LCC joint

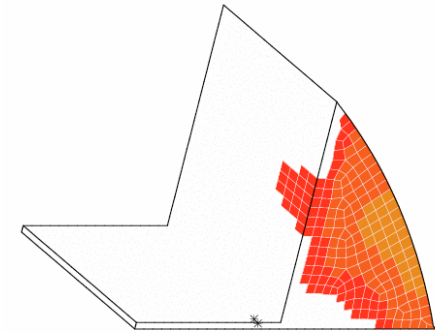
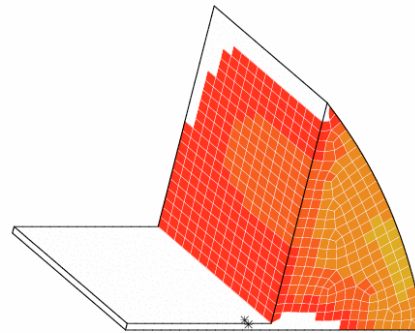
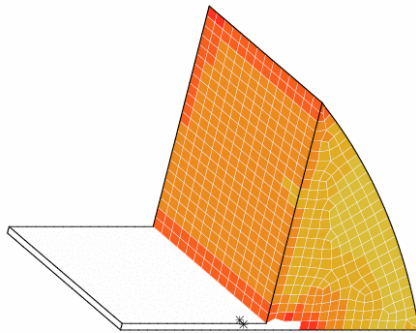


Pb-free modeling approach

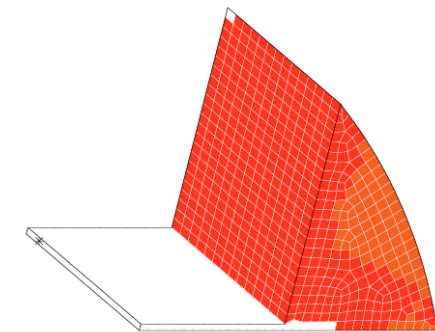
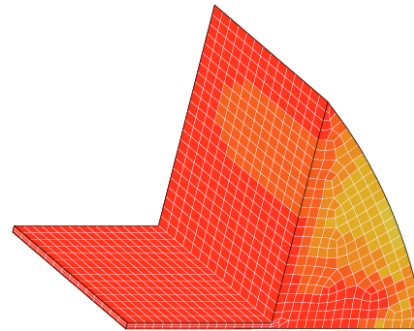
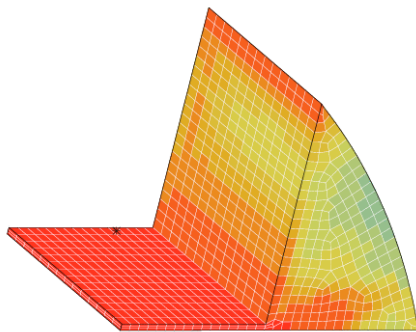
- Approach:
 - Develop Unified Creep-Plasticity Damage (UCPD) Model for the Pb-free Solder 95.5Sn-3.9Ag-0.6Cu
 - We use the modeling paradigm developed for Pb-Sn solder
 - » Microstructurally-based damage model
 - » Fracture when microstructural parameter exceeds critical value
 - Implement the constitutive model in a life prediction method (Pb-free SIP)
- The model is newer, but results are promising.

Comparing Pb-free to Pb-Sn solders

**Sn-Pb
model**



**Pb-free
model
(SAC)**



500

1000

1500 cycles

⇒ Pb-free SAC solder appears to have a longer lifetime than PbSn solder in the same joint configuration.



- ## Sn-Pb solder

Failed

Pass

Pb-free solder

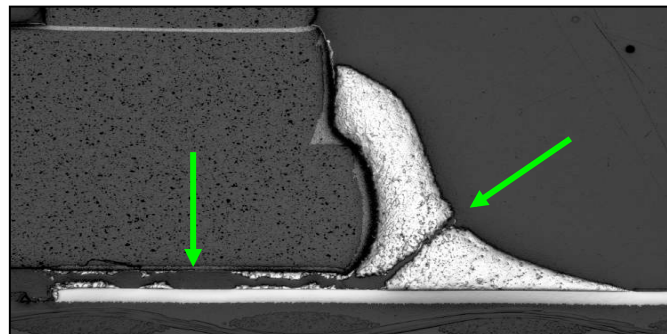
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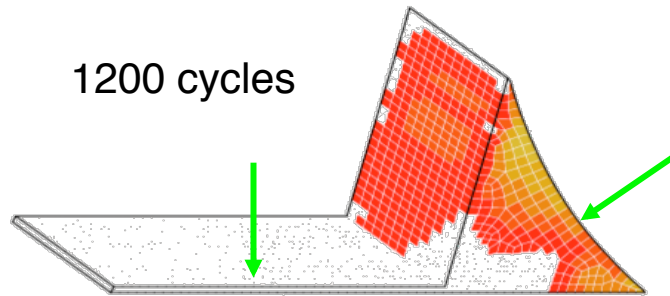
Pb-free SIP today

- Pb-free SIP is beginning to be exercised as a predictive design and analysis tool by customers at Sandia and Lockheed-Martin.

LCC Pb-free test vehicle
900 thermal cycles



1200 cycles





Summary

- Reliability of solder joints is an important design and stewardship issue.
- We have developed a desktop design and analysis package for solder joints, the Solder Interconnect Predictor (SIP)
 - Pb-Sn and Pb-free solders
 - Models entire lifetime to open circuit failure
- SIP uses experimental results to develop and to validate the model
 - Excellent agreement with experiment for both location and cycles to failure
- SIP is being used by customers to make engineering decisions in an ICME framework



Solder Constitutive Model Development

Step 1. Capture mechanical response - Elasticity, Plasticity, Creep
Effects of temperature and loading rate

Step 2. Include effects of microstructure on mechanical response
Hall-Petch effect on flow strength
Effect of coarsening on steady-state creep

Step 3. Capture evolution of microstructure - Coarsening
Temperature and mechanical loading effects
Use state variable to describe microstructure

Step 4. Failure - Lifetime prediction methodology
Failure based on state of microstructure
Coffin-Manson using plastic strain increment from fea
Continuum damage approach



A Viscoplastic Model for Solder

Constitutive Relation

$$\dot{\boldsymbol{\sigma}} = \mathbf{E} : (\mathbf{d} - \mathbf{d}^{\text{in}})$$

Inelastic Deformation Rate

$$\mathbf{d}^{\text{in}} = \frac{3}{2} \dot{\gamma} \mathbf{n} = \frac{3}{2} f \exp\left(\frac{Q}{RT}\right) \left(\frac{\lambda_0}{\lambda}\right)^p \sinh^m\left(\frac{\tau}{\alpha(c + \hat{c})}\right) \mathbf{n}$$

Normalized Stress Difference Tensor

$$\mathbf{n} = \frac{\left(\mathbf{s} - \frac{2}{3} \mathbf{B}\right)}{\tau}$$

von Mises Effective Stress

$$\tau = \sqrt{\frac{3}{2} \left(\mathbf{s} - \frac{2}{3} \mathbf{B}\right) : \left(\mathbf{s} - \frac{2}{3} \mathbf{B}\right)}$$

Evolution Eq. for State Variable c

$$\dot{c} = A_1 \dot{\gamma} - (A_2 \dot{\gamma} + A_3)(c - c_0)^2$$

Evolution Eq. for State Tensor \mathbf{B}

$$\dot{\mathbf{B}} = A_4 \mathbf{d}^{\text{in}} - (A_5 \dot{\gamma} + A_6) \sqrt{\left(\frac{2}{3} \mathbf{B} : \mathbf{B}\right)} \mathbf{B}$$

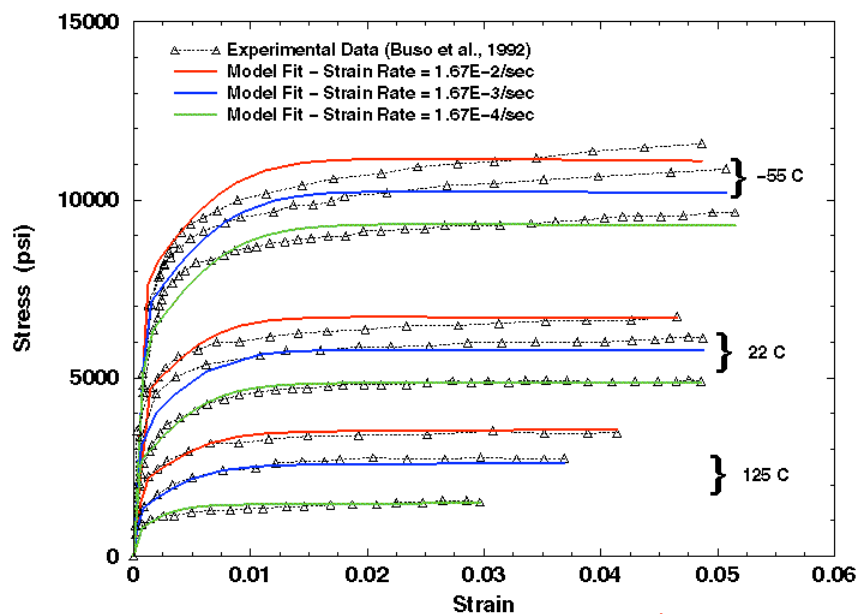
Effect of Coarsening on Strength (Hall-Petch Relationship)

$$\hat{c} = A_7 \left(\frac{\lambda_0}{\lambda}\right)^{A_8} \quad A_3 = \frac{1}{2}$$

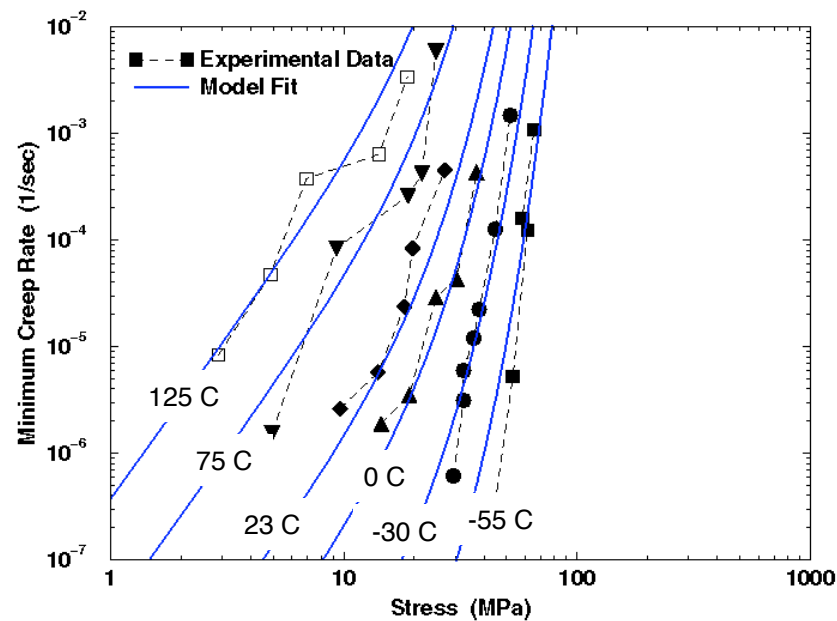
Coarsening Rate (Pb-rich Phase Size)

$$\dot{\lambda} = \frac{(A_9 + A_{10} \dot{\gamma})}{(\lambda - \lambda_0)^{A_{11}}}$$

Constitutive Model vs. Experimental Data

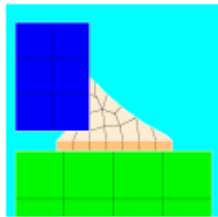


Uniaxial Compression



Steady-State Creep

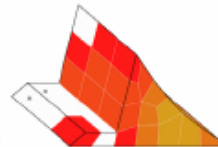
How significant is mesh dependence?



42 solder elements



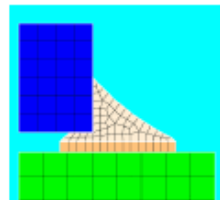
4,100 cycles



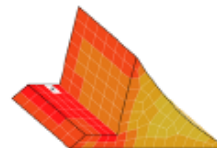
5,100 cycles



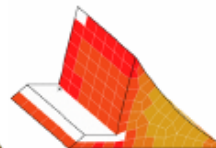
9,100 cycles



318 solder elements



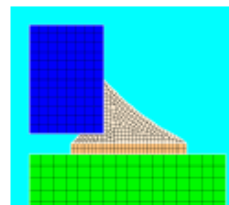
3,100 cycles



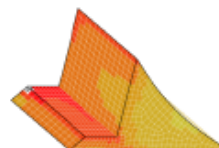
4,500 cycles



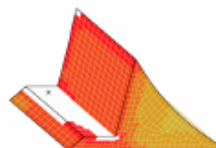
8,400 cycles



2,782 solder elements



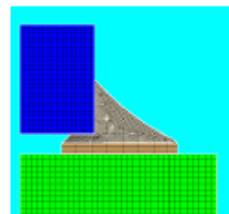
2,200 cycles



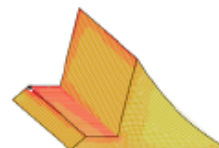
3,600 cycles



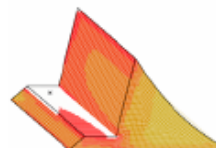
7,600 cycles



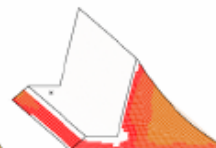
22,152 solder elements



1,600 cycles



2,900 cycles



7,100 cycles

- Mesh dependence is minimal for cracking via weak elastic elements.